Mini-STEP

A Minima] Satellite'J'est of the Equivalence Principle Experiment

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1. Introduction and summary

The Mini-STEP concept was conceived from a desire by NASA to reduce the cost of the Satellite Test of the Equivalence Principle (STEP) experiment below that of the already downsized Quick STEP concept. The goal was for the total cost, including payload, spacecraft, launch vehicle, reserves and operations to be in the $50 m range. Stanford University and the Jet Propulsion Lab studied this simplified STEP concept between March and June 1995. A similar concept was developed in parallel by the European Space Agency (ESA) as an alternative to the M3 STEP mission.

The Mini-STEP approach was to start with the Quick STEP concept, define the minimum science floor anti then reduce every component to be the smallest and least expensive available, consistent with the minimum science objectives. The most expensive items in Quick STEP were the instruments, spacecraft and launch vehicle, in that order. The payload was reduced from four differential accelerometers and a gradiometer to just four differential accelerometers (from ten to eight test masses). A semi-production spacecraft planned for a communications constellation was selected for its low cost, small size and simplicity. The total system mass of 390 kg allows the use of a less expensive shared Taurus launch vehicle which can place the payload in a 400 km, sun-synchronous polar orbit. Due to the simpler payload, the minimum mission duration is reduced to less than four months. 1 lowever, the primary experiment of measuring the Equivalence Principle to 10^{-18} is unchanged, In addition, the geodesy experiment was eliminated.

Stanford University will design and build the payload with the likelihood of international collaboration in mission and payload subsystem components. NASA will manage the project through the Jet I'repulsion Laboratory.

2. Mini-STEP Science. Objectives

Simply stated, the Equivalence Principle says that gravitational and inertial mass arc equivalent measures of the same thing. The Satellite Test of the Equivalence Principle (STEP) compares the ratios of inertial to gravitational mass to an unprecedented accuracy. The "Weak" Equivalence Principle (WEP) postulates that all test objects in an external gravitational field fall with the same acceleration, independent of their composition. The primary scientific objective of STEP is to measure any difference in the rate of free fall of test masses of different compositions in an Earth orbiting satellite to one part in 10]8 of the total gravitational acceleration. This is approximately a million-fold improvement in sensitivity over the best experiments to date. While Quick STEP had four differential accelerometers that could compare four different materials simultaneously, only a single differential accelerometer is required to carry out the experiment. Mini-STEP also uses four differential accelerometers, but they arc operated sequentially to reduce the number of electronic components. Either four or five test materials can be used with the four differential accelerometers.

The earlier Quick S“1’}{1’ concept used the (img,-free properties of the satellite, a precision gradiometer and the precise position determination capability of the Global Positioning System (GPS) to conduct a geodesy experiment. The geodesy experiment and its gradiometer as well as the GPS receiver is dropped from the Mini-S’1’1{1’ mission.

The reduced science requirements and simplified payload configuration significantly reduce the overall system requirements. The mission duration is reduced from six to four months since thei c arc fewer measurements to be made. Spacecraft pointing is reduced from 10 arcseconds to one arcminute and the data rate is reduced from 315 bit/s to 128 bit/s. Payload weight and power have correspondingly large decreases.

3. Payload

The core of the Mini-STEP payload is the superfluid helium dewar enclosing the probe that contains the experiment apparatus. A smaller liquid helium dewar consistent with the smaller payload and shorter mission was investigated. It turned out that the Quick STEP dewar, an existing design by Lockheed, is less expensive than developing a new dewar and could be accommodated by the preferred Taurus launch vehicle shroud.

The dewar provides the required 1.8 K temperature within the experiment volume by employing four vapor-cooled shells. The nominal temperature of the outermost shell is 200 K with a mass flow rate of the helium gas of 1.6 mg/sec. The helium boil-off gas is collected into a reservoir. The gas is then routed, under computer control, to 16 thrusters that provide the force anti torque required to maintain the satellite drag-free in both translation and rotation. The drag-free sensors arc the two payload differential accelerometers which provide sensing in the X and Y directions through common mode measurements in their sensitive axes. Sensing in the Z direction (normal to the orbits] plane) is done by capacitive measurements in the accelerometer’s radial direction. The calculated rate of helium gas boil-off and the chosen thruster configuration provides an upper force limit in any direction of about 160 dynes. The payload geometry is shown in figure 1.

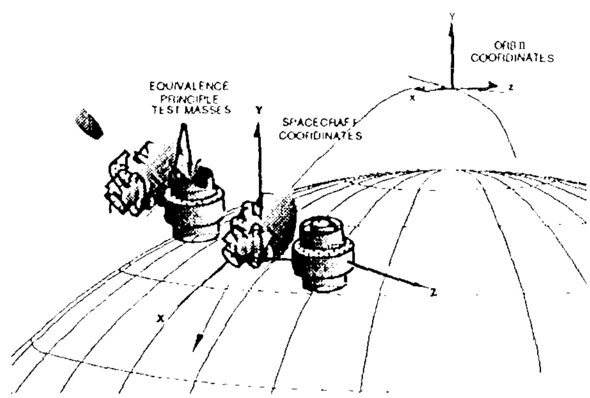

Figure 1. Mini-STEP payload geometry

The Mini-STEP differential accelerometers arc housed in a quartz block, similar to, but smaller than Quick STEP. Only one accelerometer will be operated at a time, therefore only one set of payload electronics is provided (compared to five for Quick STEP). The gravitational effect of helium slosh on the differential accelerometers is easily avoided in Mini-STEP by confining a reduced volume of helium in the dewar to a radius of greater than 25 cm from the test masses. Otherwise the configuration of the dewar, accelerometer package, warm electronics and solar panels is similar to Quick STEP.

4. The Spacecraft

Figure 2 shows the overall configuration of the Mini-STEP satellite including the payload and spacecraft.

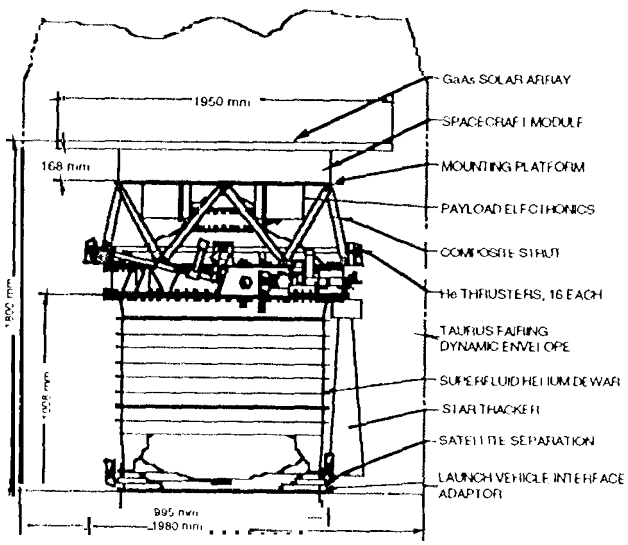

Figure 2. The Mini-STEP Satellite

The baseline spacecraft is a commercial lightsat presently being developed as a global communications network. Two satellites were successful] y launched in 1995. The lightsat is carried on top of the payload and only provides such basic services as power, command and data handling, telemetry and tbc central computer. Modifications to the standard spacecraft include removal of the attitude control system, inclusion of the optional S-band telemetry system and a single, 1.95 m diameter, silicon solar array. The solar array is mounted on top of the spacecraft. and provides >200 w power. There is sufficient space inside the spacecraft to contain the warm payload electronics, therefore no additional electronics pallet is required as in Quick STEP. The launcher interface adapter attaches to the dewar lower mounting ring. The thermal control is passive, using conventional means (multilayer insulation and paints) to maintain the equipment temperature within limits. The dewar sides arc covered with multilayer insulation (Ml,]). The solar array shields the dewar from direct solar radiation, while the Ml,1 covers protect it from the Earth radiation. Temperature excursions on the dewar outer shell due to the changing attitude with respect to the Earth arc maintained well below I K, ensuring high thermal stability anti very low structure deformation at orbital frequency.

Coarse attitude sensors include two star trackers, sun sensors and magnetometers. Attitude control of Mini-STEP is relaxed to one arcminute and will be provided completely by the payload (irag-free thruster system and payload computer.

A single battery is used in the early attitude acquisition phase and for emergency energy provision to life-critical equipment. S-band communication with the ground stations is provided by two hemispheric coverage antennas located on opposite edges of the spacecraft. The DSN antennas provide high margins for telemetry with a spacecraft transmitter power of less than 1 Watt and an average data rate of 128 bits/see. The onboard data handling is managed by a central processing unit collecting the science and control data into a solid state 320 megabyte mass memory.

5. The Mini-STEP Mission

A lower limit to the orbital altitude is set by the atmospheric drag force, since the helium boil-off can cancel only a limited drag. A sun synchronous orbit, free of eclipse for the six-month duration of the mission, is necessary, to avoid large changes in the beat input that might Cause thermoelastic deformation of the structure. such deformations would cause changes in the self gravity of the satellite at orbital frequency which would be detected by the accelerometers, and have the same signature as an Equivalence Principle violation signal.

The planned orbit has an altitude of approximately 400 km and an inclination of 97.1 degrees. To avoid eclipses, the satellite must be launched within one of two yearly launch windows, each two months long and centered around the equinoxes. The daily launch window is one hour wide and is chosen to place the sun at right angles with respect to the orbit line of nodes. The currently assumed launch epoch is the fall of 2000 with a four month operational period.

The satellite will be launched by a shard Taurus launch vehicle from the Western Test Range (Vandenberg Air Force Base). A large mass margin is available from this launcher with respect to the planned satellite mass of 388 kg. The only present launch vehicle less expensive than the shared Taurus is the Pegasus. Pegasus can place less than 300 kg into the required orbit. Every attempt was made to reduce the Mini-STEP mass so that the Pegasus launch vehicle could be used. It finally became hopeless when it was realized that the solid-fuel Pegasus needed a costly and heavy Hydrazine Auxiliary Propulsion System (HAPS) to circularize the orbit.

The basic attitude mode of the satellite (Normal or N-mode) is inertial, with the Z axis pointing at the orbit normal. The sensitive axis of the reference accelerometer is in the orbit plane, and points parallel to the orbital velocity vector as the satellite passes over the highest latitude point in its orbit. '1'bus, the signal one wants to measure is nominally a sinusoid. Other attitude modes arc used to (distinguish the Equivalence Principle violation signal from signals, originating, either in the spacecraft or in the environment, that have the same (orbital) frequency when the satellite is in N-mode. The turning or T-mode has the spacecraft rotating at a constant rate (from half to twice the orbit rate) about the Z axis. Spurious signals arc distinguished by their changing amplitude, phase anti frequency as the satellite is moved from one mode to another.

The planned mission profile includes a basic measurement cycle with the satellite spending one week in each of the two basic attitude modes. A two-tcl-three week-long period of checks for systematic disturbances follows, when both attitude modes can be used, anti then the basic cycle is repeated. The initial commissioning and calibration phase is estimated to last two weeks. The mission lifetime is limited by the time it takes to evaporate the superfluid helium cryogen in the dewar. The baseline dewar design provides a four months supply with a total liquid helium capacity of about 120 liters. Table 1 compares the main features of the earlier Quick STEP mission with the new Mini-STEP

Table 1. Quick STEP and Mini-STEP mission comparison

	Quick STEP	Mini-STEP
Launch Vehicle	Taurus	shared Taurus
Payload Capability@400km	**900** kg	≈ half of 950 kg
Spacecraft	"Lightsat"	OSC Microstar
Type	3-axis stabilized to 10 arcsec	ACS by 1'/1, to 1 arcmin
Mass	120 kg	35 kg
Power available	>200 w	>200 w
Telemetry	S-band @ S Mbps	S-band @ 5 Mbps
Cost	< $25 M	≈ $4 M
Payload (with helium)		
Mass	386 kg	310 kg
Average power	105 w	98 w
No. of accelerometers	6	4
No. of test masses	10	8
Data rate	315 bits/sec	128 bits/see science
Mission		
orbit	500 km circular	400 km circular
Lifetime	< 6 months	<4 months
Total launch mass	600 kg	388 kg
Launch date	Spring, 2000	Fall 2000

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